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The effects of a high energy pulsed laser induced shock wave on the properties and microstructure of a series of titanium vanadium alloys were investigated. The peak pressure of the shock waves was increased by using high acoustic impedance back-up plates and by splitting the laser beam to shock two opposite sides of the specimen simultaneously. The hardness and strength of the alloys were increased up to 10 percent after laser shocking. The shock hardening was attributed to shock induced dislocations and twinning, and

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possibly strain transformed metastable β depending on alloy composition and heat treatment. The magnetic susceptibility of the alloys was unaffected by laser shocking.

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FINAL REPORT

on

PULSED LASER INTERACTIONS WITH TITANIUM-VANADIUM ALLOYS

to

U. S. ARMY RESEARCH OFFICE
Grant No. DAAG29-77-G-0187
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by

A. H. Clauer and B. P. Fairand

February 15, 1979

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Statement of the Problem

Irradiation of metals by a high energy pulsed laser beam creates a high surface pressure which then propagates into the metal as a high amplitude stress wave. These high amplitude stress waves constitute a shock wave that has the capability to modify the metal's microstructure and properties through various energy absorption mechanisms. Substantial changes in mechanical properties of aluminum and iron alloys have already been shown to be caused by high shock-induced dislocation densities, i.e., strain hardening. There also exists the possibility for shock-induced strain transformations which offers additional mechanisms for microstructure and property modification by laser induced shock waves. The objective of this investigation was to study the pulsed laser–shock interactions with a series of Ti-V alloys having the potential to show shock induced phase transformations, and in addition to develop laser shocking arrangements to increase the peak shock pressures.

Important Results

Two laser shocking configurations were investigated to increase the peak pressure of the laser-induced shock waves. One was to use a high acoustic impedance tungsten back-up plate to reflect the shock wave from the front surface of the specimen back into the specimen at a higher pressure amplitude. The other was to split the laser beam and irradiate both front and back surfaces simultaneously, creating a superposition of the two shock waves with an attendent pressure increase in the center of the specimen thickness. Both of these methods were effective, giving peak pressures greater than 10 GPa (100 kbar).

Both hardness and tensile strength were increased in these alloys by laser shocking, with the largest increases being about 10 percent. The pressure enhancement arrangements were required to get these increases. The results suggest that the acoustic impedance method causes greater hardening even though the calculated peak pressure is lower. This is possibly due to the longer shock pulse duration used in the acoustic impedance experiments.

Magnetic susceptibility measurements to determine relative amounts of the constituent phases in the Ti-V alloys raised some questions concerning the sensitivity of the technique to the constituent phases compared to compositional changes. The quenched and furnace cooled alloys had quite different microstructures for vanadium contents of 15 and 20 weight percent, yet the magnetic susceptibility measurements were similar. No effects of laser shocking on magnetic susceptibility were found.

The changes in hardness and strength of the quenched α', martensitic, and $\beta + \omega$ alloys is attributed to a combinations of shock strain hardening and strain induced transformation of metastable β to martensite. The changes in hardness and strength of the furnace cooled, $\alpha + \beta$ alloys is attributed to shock strain hardening. It is probable that phase transformations other than the martensitic transformation did not occur because the peak pressures and pulse durations developed in this program were not large enough.

Publications

"Laser Generation of High Amplitude Stress Waves in Materials", B. P. Fairand and A. H. Clauer, accepted for publication in J. of Appl. Physics, Spring 1979.

"Laser Shocking of Titanium-Vanadium Alloys", A. H. Clauer, and B. P. Fairand, in preparation.

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INTRODUCTION

Recent studies have shown that irradiation of metals by high energy pulsed lasers can induce high amplitude stress waves in metals.[1-6] Studies at Battelle have shown that these stress waves have a significant effect on the microstructure and properties of metals.[7-12] The tensile strength of aluminum alloys[12], particularly welded alloys[9], has been substantially increased, and the hardness of aluminum alloys[12] and stainless steel[10] has been increased by laser shocking. In addition, the fretting fatigue life of aluminum alloys has been significantly increased[12] as well as the fatigue life of a welded aluminum alloy.[11] Transmission electron microscopy of thin foils of these metals before and after laser shocking has shown that the dislocation microstructures produced by the laser-induced stress wave is similar to those observed after shocking using other techniques.[12]

A computer code for predicting the laser-induced pressure environment on the surface of a specimen during irradiation was developed in earlier programs at Battelle and extended in this program. This code

predicts the pressure-time profile of the surface pressure, given the laser beam parameters and appropriate material properties. The predicted peak pressures are in good agreement with measured values and indicate that peak pressures of 10 GPa and higher might be attained.

These observations of the substantial peak shock wave pressures and in-material microstructure and property changes suggested that these laser-material interaction studies be extended from shock induced dislocation hardening alone to alloy systems having the potential for shock induced phase transformations. In metals which have a polymorphic phase transformation at pressures above the ambient, a shock wave may induce the phase transformation in addition to plastic deformation. If the new phase is retained after passage of the shock wave it obviously would change the material properties. However, even if it reverts back to the low pressure equilibrium phase after shocking, large concentrations of lattic defects are often introduced by the transformation, which also influence material properties, particularly strength, hardness, and ductility.

The study of shock induced phase transformations is a difficult one and the investigation of the formation and identification of shock induced phases require sophisticated instrumentation. The question of pulse duration, over-drive pressure, pressure release, temperature, shear stress and others as they effect the amount of transformation product and its retention to room temperature are all important.[13] In this study we used the highest possible laser generated peak pressures and different pulse durations to attempt to reach the necessary conditions to induce a phase transformation in the titanium-vanadium alloys selected.

In titanium and its alloys there is evidence that a pressure-induced transformation does occur. Bridgeman[14] first suspected its presence at 35 kbar pressure during static pressure experiments on titanium and later Jamieson[15] detected it at higher pressures and identified it as the same phase as the ω phase observed by Silcock[16] and Bogaryatskii, et al[17] in titanium-vanadium and titanium-chromium alloys. He also found that this phase persisted at room temperature after releasing the pressure, but could be completely converted to the h.c.p. α by heating to 110 C for 17 hours. Bundy[18] extended these experiments over a wide range of temperature and pressure and developed a pressure-temperature (P,T) diagram showing the $\alpha \rightleftarrows \omega$, $\alpha \rightleftarrows \beta$, and $\beta \rightleftarrows \omega$ phase boundaries for titanium. The $\alpha \rightleftarrows \omega$

transition pressure was located at 90 to 95 kbars over the temperature range 20 to 630 C. The other transitions were located at higher temperatures. From a study of a series of Ti-Nb alloys pressurized at room temperature, Afonikova, et al[19] suggested that the equilibrium $\alpha \rightleftarrows \omega$ transition pressure should be at 20 to 30 kbar, but the sluggishness of the reaction made its determination difficult. In Ti-10 at/o Nb they reported complete conversion to ω at 100 kbar and higher. They suggest that the phase lines given by Bundy[18] represent complete conversion to ω and not the equilibrium transition pressure.

In shock wave experiments, the probable existence of a phase transformation has been shown, but the resulting phase has not been identified. Carter[20] detected a phase transition at about 188 kbar in shocked titanium. This is far above the static threshold pressures. Koul and Breedis[21] shocked Ti and a series of Ti-Mo alloys at peak pressures of 70 and 200 kbar. In Ti, a study of the shocked microstructure, strength and hardness, led them to the conclusion that a phase transformation had occurred during the 200 kbar shock, but since no retained ω was detected after the shock they suggested that β had formed during the shock and retransformed to α' martensite after the shock, i.e., the sequence was $\alpha' \rightarrow \beta \rightarrow \alpha'$. For the Ti-9w/oMo alloy they suggested $\alpha' \rightarrow \beta \rightarrow \alpha'$ during the 200 kbar shock. In a Ti-12w/oNb alloy having a structure of metastable β, Koul and Breedis found predominantly $\beta + \omega$ present after shocking. They attribute their resultant microstructure and strength properties to stress-induced martensite although attempts to identify it were not conclusive.

Some support for the suggestion that a pressure-induced $\beta \rightleftarrows \omega$ transition occurs at lower temperatures in Ti alloys than is indicated by Bundy's[18] diagram, is taken from the reports that large compressive deformations of Ti-15 w/oV[22] and Ti-15w/oMo[23] lead to the formation of ω phase by the reaction, metastable $\beta \rightarrow \omega$. Large compressive strains were involved and the hydrostatic pressures must have been under 10 kbar. On the other hand, neither very light compressive deformation or tensile deformation resulted in ω formation from the β phase in Ti-13w/oMo or Ti-29w/oV alloys[24].

To investigate the effects of laser shocking on microstructure and material properties including the influence of possible shock induced phase transformations, a series of titanium-vanadium alloys was selected. With increasing vanadium content the ω phase precipitates as a metastable phase above about 12 weight percent V.[25] Therefore it would be expected that the transformation pressure for $\alpha \rightleftarrows \omega$ and $\beta \rightleftarrows \omega$ would decrease with increasing vanadium, and shock induced transformations might be evident at the higher vanadium concentrations. In addition, the metastable retained β in quenched alloys is prone to transforming to martensite under the influence of the plastic strain associated with the shock wave, providing further interesting effects on properties and microstructure.

OBJECTIVE

The objective of the proposed research was to investigate pulsed laser-material interactions in Ti-V alloys, including both the generation of shock waves and energy absorption and material damage mechanisms as they relate to property and microstructural changes originating from plastic deformation and phase transitions. Specific objectives were (1) to achieve the highest and longest sustained shock pressures possible with the existing facilities, (2) to determine the extent of mechanical property degradation or improvements caused by the laser shocking, and (3) where possible, identify the mechanisms governing the material response, including any phase changes that occur during shocking and their relation to alloy composition and starting microstructure.

MATERIAL

Titanium and a series of titanium-vanadium alloys were studied. The titanium was obtained in the form of 0.025 mm thick foil and 3 mm thick sheet of commercial purity. The Ti-V alloys were prepared by consumable electrode melting twice into final ingot form, 7.5 cm diameter by 11.5 cm long. The final compositions of the alloys were Ti-4.3V, Ti-11.3V, Ti-14.6V and Ti19.9V, in weight percent. Oxygen for all four alloys was in the range 0.17 to 0.20 weight percent.

The ingots were sectioned and homogenized 48 hours at 1100 C followed either by iced brine quenching to form martensite or $\omega + \beta$ phase microstructures, or furnace cooling to avoid the martensite and form a more nearly equilibrium $\alpha + \beta$ phase microstructure.

Discs 2.5 cm in diameter by 0.1 cm thick were machined from these homogenized ingot sections for subsequent laser shock studies. After machining, the discs were ground to 0.2 to 0.5 mm thickness on #600 paper before laser shocking.

To provide adequate material for tensile specimens, the ingot sections of each alloy were worked into strip 4.5 cm wide and 0.08 cm thick by hot forging and hot rolling to 0.13 cm thickness followed by cold rolling to the final thickness. The resulting strip was heated to 500 C for 0.5 hour, air cooled and straightened, then cleaned, surface ground, encapsulated in argon and heated 1 hour at 1100 C followed by either an ice brine quench or an air cool within the capsule. This heat treatment was to develop microstructures similar to the cast material. The heat treated strips were then machined into tensile specimens 0.05 cm thick having a gage section 1.5 cm long by 0.5 cm wide.

EXPERIMENTAL PROCEDURE

Laser Irradiations

Laser shocking of the specimens was performed in two ways. One method, used for the discs, was to irradiate the specimens from one side only with the specimen backed up by a titanium or tungsten back-up plate,

or by a quartz pressure gauge. The other method, used for both discs and all of the tensile specimens, was to split the laser beam into two beams and irradiate both sides of the specimen simultaneously. The laser beam(s) were focused to the desired spot diamter, 1.1 to 1.5 cm, using 1-meter focal length lenses.

The laser energy incident on the specimens was determined by first measuring the energy at the irradiation site with CGE carbon calorimeters. These measurements were used to standardize other carbon calorimeters which monitor the output of the laser during each shot. This monitoring was done by splitting off a small fraction of the laser energy and directing it to these on-line calorimeters. The shape of the laser pulse emitted by the last laser amplifier was also monitored during each shot by using a beam splitter to direct a small amount of laser energy to a photodiode whose output was displayed on a fast oscilloscope. Figure 1 shows a typical laser pulse measured with this setup. The laser pulse duration is obtained from the pulse width at half the peak height. The pulse durations used in this study were in the range of 20 to 70 nsec.

Before the specimens were laser shocked, their surfaces were first covered with a thin layer of acrylic black spray paint and then 0.3 cm thick by 3.8 cm diameter quartz discs were clamped over the surfaces to be laser irradiated.

Material Studies

Optical metallography was used to establish the initial microstructures of the alloys. The microstructural effects of laser shocking were studied primarily using transmission electron microscopy. Hardness changes were determined using Vickers diamond pyramid microhardness (DPH) with a 0.5 kg load. Tensile tests were conducted at room temperature at an initial tensile strain rate of 0.002 min^{-1}.

EXPERIMENTAL RESULTS

Laser Induced Pressure Environments

A significant part of the research in this area concentrated on techniques for generating high pressures to provide the greatest possibility

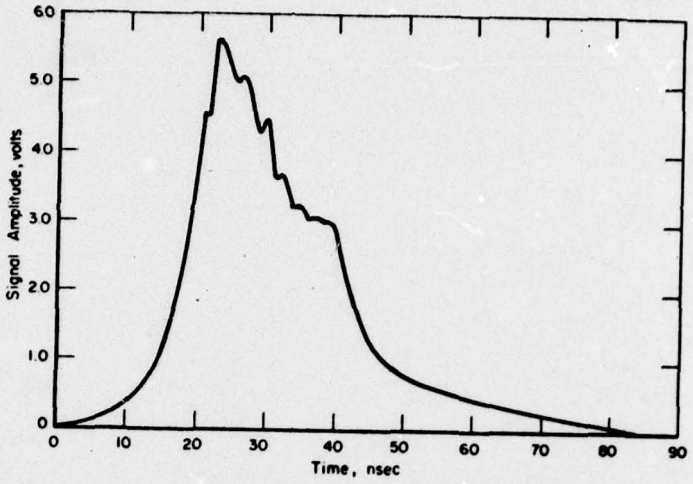

FIGURE 1. TYPICAL LASER PULSE SHAPE USED IN THIS STUDY

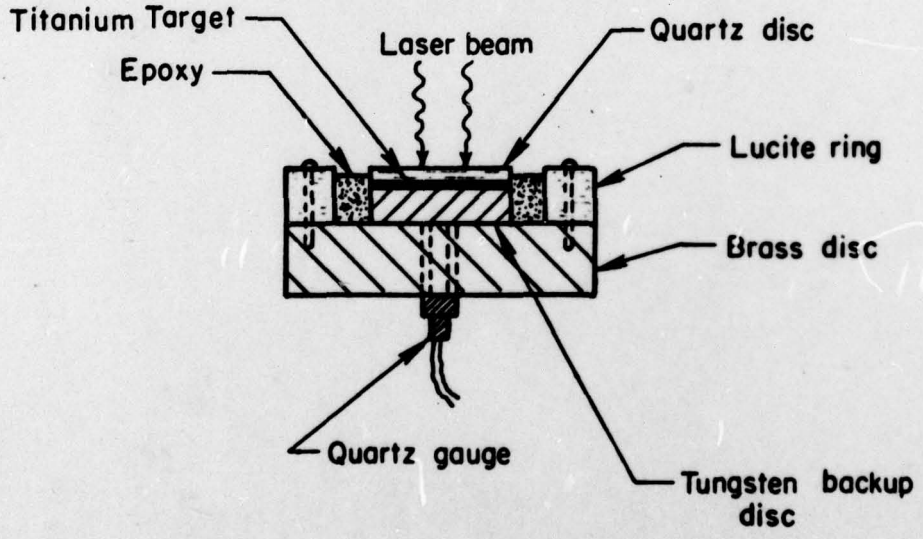

FIGURE 2. TARGET CONFIGURATION AND PRESSURE MEASUREMENT ARRANGEMENT FOR THE DELAYED ACOUSTIC PULSE EXPERIMENTS

for generating material microstructure and property changes. Experimental measurements and theoretical calculations were used to evaluate the laser generated stress wave environments.

For single side irradiations quartz piezoelectric pressure transducers were used to successfully measure pressures up to about 5 GPa (50 kbar) in amplitude (approximate upper limit for use of quartz transducers). Attempts to measure higher pressures and in-material pressure environments with manganin piezoresistant transducers were unsuccessful due to the limited response time of these gauges.

The computed pressure environments generated with a one-dimensional radiation hydrodynamic computer code were in excellent agreement with quartz transducer data. For this reason, the code was used to evaluate the laser and specimen conditions that would produce the high amplitude stress waves needed to create possible phase transformations in titanium-vanadium alloys. Two methods were found to be effective in generating peak pressures above 10 GPa. One method involved splitting the laser beam into two equal components and directing these two beams onto the specimen surfaces in order to simultaneously generate stress waves at both surfaces. These stress waves propagate into the specimen and superimpose near the center of the target with a resultant increase in pressure of about a factor of 2. The other technique utilized a high acoustic impedance material (tungsten) which was placed on one surface of the specimen. The other surface was shocked with the laser. The stress generated at this surface propagates through the target and is amplified at the high impedance barrier (the titanium-tungsten interface) where it is reflected as a compressive pulse. Both of these approaches gave calculated pressures greater than 10 GPa. These experiments and the analysis are described in detail in a publication accepted by the Journal of Applied Physics, Reference 6.

Delayed Acoustic Pulse Experiments

Delayed acoustic pulse experiments were performed in an attempt to dynamically probe the laser shocked region of the titanium-vanadium specimens. The procedure was to split off 10 percent of the laser beam, run this beam through an optical delay path and impinge it on the specimen surface shortly after the specimen was shocked by the main portion of the beam. The objective was to use the low intensity delayed beam to generate an elastic

wave (acoustic pulse) in the specimen which would probe the region behind the shock front. By varying the shock pressures and acoustic pulse delay time, it was hoped that a pressure induced phase transformation would be manifested by a change in the transit time of the acoustic pulse through the shocked material.

The target configuration and method of measuring the pressure wave which propagates through the specimen are shown in Figure 2. Tungsten, a high acoustic impedance material, was placed at the back surface of the thin titanium disc to increase the peak pressure in the specimen (Reference 6). The quartz transducer was used to measure the pressure pulses generated in the titanium specimen and propagated through the tungsten backup.

The measured pressure environments showed no discernable evidence of a time delayed acoustic pulse. Dispersion of the pressure waves by the tungsten backup or acoustic uncoupling of the titanium-vanadium target from the tungsten before the arrival of the trailing acoustic pulse are possible reasons for the lack of success of these experiments.

Material Response

Microstructure

The initial microstructures of the alloys were as follows. The brine quenched Ti-4V and Ti-11V alloys were martensitic. The martensite would be the hexagonal, α', phase. The Ti-15V and Ti-20V alloys appeared to consist of the body centered cubic β phase only. Unlike reports of other investigations of quenched alloys of similar compositions, the hexagonal ω phase was not detected in these alloys either by x-ray or electron diffraction techniques. This difference might be attributed to the higher oxygen content of the alloys in this study lowering the temperature for ω precipitation to sub zero temperature[26], but was more likely due to the quenched ω precipitates being too small to give distinguishable electron or x-ray diffraction evidence. The other studies aged the ω phase to obtain larger precipitates. Hardness results to be discussed later show a large peak at Ti-15V which indicates that a fine dispersion of ω was present.

The furnace cooled alloys had quite different microstructures. The Ti-4V and Ti-11V alloys consisted of lamellar hexagonal close packed α

phase plus β phase. The Ti-15V and Ti-20V alloys had a much finer lamellar structure which was not analyzed but would be expected to consist of α + β transformed at lower temperatures due to the increased alloy content.

The microstructural changes resulting from laser shocking were investigated by electron transmission microscopy in foils prepared from 0.5 mm thick discs shocked with the split beam technique to increase the peak pressures in the material. The calculated peak pressures were 6.0 to 6.5 GPa with a pulse length of 25 ns. Therefore the peak pressure in the center of these thin discs was over 10 GPa (Reference 6, Figures 6 and 7). In each case no definitive differences could be discerned between the shocked and unshocked microstructures, with the possible exception that the Ti-20V alloy had a somewhat higher dislocation density after shocking than before shocking. The Ti-15V alloy was difficult to thin and good microstructures were not obtained. The difficulty in seeing microstructural changes which can be attributed to laser shocking is due to the already complex martensite microstructure in the Ti-4V and Ti-11V alloys. The absence of substantial microstructural changes in the Ti-20V alloys is puzzling. Neither strain-induced martensite nor a significantly higher dislocation density were observed in the foils examined after laser shocking, although optical metallography showed that this alloy is prone to strain induced transformations.

Magnetic Susceptibility

Collings[27] Suggested that the magnetic succeptibility of quenched Ti-V alloys could be correlated with the relative fractions of α', α, β and ω phases. Because of the difficulty of measuring the relative amounts of the various phases metallographically, magnetic susceptibility measurements were included in this program to determine whether changes in magnetic susceptibility after laser shocking would correlate with shock induced phase transformations.

Magnetic susceptibility measurements were made on both the brine quenched and furnace cooled materials with and without laser shocking. The results are shown in Figure 3. The peak pressures on the brine quenched alloys ranged from 4 to 7 GPa whereas the peak pressures on the furnace cooled specimens were all within the range 7 to 7.5 GPa. In the unshocked condition, the quenched alloys are in good agreement with Colling's results, being within the data scatter of the original curve. The furnace cooled

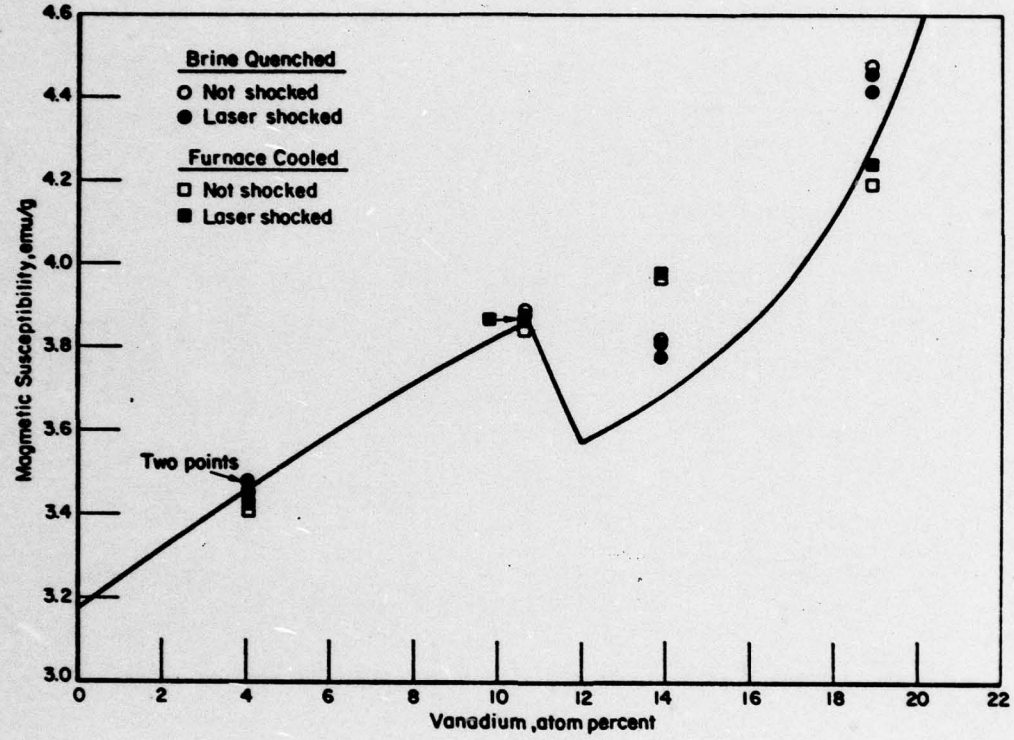

FIGURE 3. THE INFLUENCE OF LASER SHOCKING AND HEAT TREATMENT ON THE MAGNETIC SUSCEPTIBILITY OF THE Ti-V ALLOYS

The solid line is taken from the original curve by Collings[27].

alloys lie along the curve for the alloys containing 11V or less, but the higher vanadium content alloys lie on either side of the curve. Collings suggested that the dip in magnetic susceptibility at 15V was caused by the presence of the ω phase. According to Hickman[25] this quenched alloy is estimated to contain 70 volume percent ω phase. Our alloys may contain somewhat less than this because of the higher oxygen content. The increase in magnetic susceptibility at higher vanadium contents reflects decreasing amounts of ω phase. Any laser induced transformations of α or β to ω in a given alloy would result in a decrease in magnetic susceptibility.

Since the furnace cooled alloys are a mixture of α and β and the magnetic susceptibility results of the Ti-15V and Ti-20V alloys appear to lie on the extension of the low vanadium curve, which would consist of α' and retained β, perhaps this trend reflects the continuous change in the α + β content of these alloys. An interesting point here is that the furnace cooled α + β alloys lie on the same curve with the quenched α' alloys. There are several different reaons to rationalize this trend, including either that an alloy in both heat treat conditions contains a similar volume fraction of β, or that the measurement is not sensitive to relatively small differences in phase content. There is too little data to do more than speculate.

More important, in no case did laser shocking change the magnetic susceptibility by more than the specimen to specimen differences. Therefore any phase transformation was only within the sensitivity of the technique. The comparison of the brine quenched and furnace cooled alloys in this study suggests that magnetic susceptibility is sensitive only to relatively large changes in the volume fraction of the constituent phases and is possibly more sensitive to overall compositional changes.

Hardness

A relatively easy and inexpensive way to assess the effect of laser shocking on mechanical strength properties are hardness measurements. Microhardness is required because the discs are very thin. The effect of the two methods of increasing the peak pressures was assessed by measuring the microhardness of the discs after laser shocking by each method.

The effect of using a back up material with a high acoustic impedance is shown in Figure 4. Tungsten has a much higher acoustic impedance than titanium and the W-Ti interface reflects the shock wave back into the Ti-V disc with increased peak pressure (Reference 6), whereas

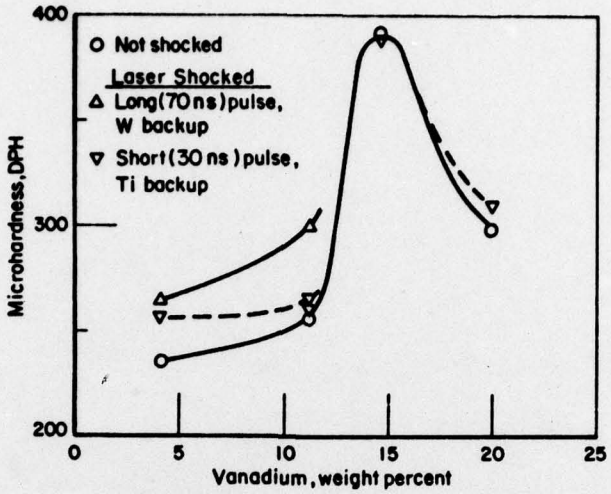

FIGURE 4. CHANGE IN HARDNESS AFTER LASER SHOCKING ON ONE SIDE ONLY WITH BACK-UP MATERIALS HAVING DIFFERENT ACOUSTIC IMPEDANCES

The range of front surface peak pressures is 5.0 to 6.7 GPa. The alloys are homogenized and quenched.

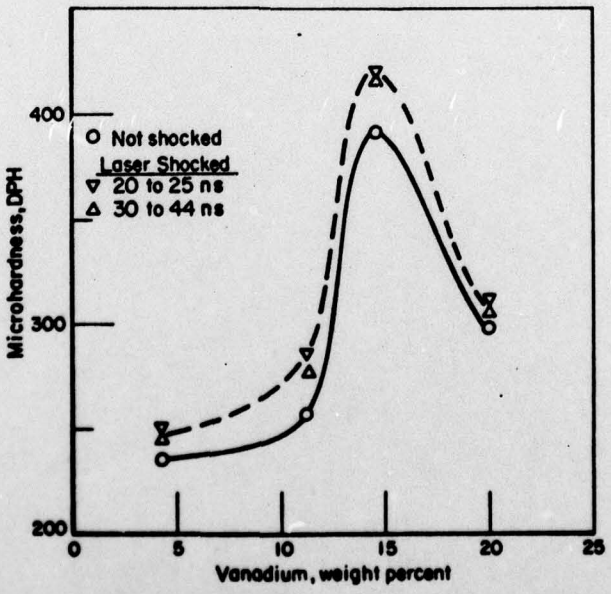

FIGURE 5. CHANGE IN HARDNESS AFTER LASER SHOCKING BOTH SIDES SIMULTANEOUSLY WITH A SPLIT BEAM

The peak pressures range from 5.5 to 7.4 GPa with most of the 20 to 25 ns shots being at 6.2 GPa. The alloys are homogenized and quenched.

the titanium back-up plate has effectively the same impedance as the Ti-V disc and the TiV-Ti interface will not reflect the shock wave. The tungsten back-up plate increases the hardness more than the titanium back-up (Figure 4), as expected from the higher peak pressures developed with the tungsten back-up. Some of the enhanced hardening might be due to the longer pulse, but the effects of pulse length may not be very large, as suggested later by the split beam results. The titanium back-up has little effect for vanadium contents of 11 percent and above.

The other laser shocking configuration, splitting the laser beam to shock both sides simultaneously, is intermediate in increasing the hardness as shown in Figure 5. The results of laser shocking two separate series of 0.5 mm thick specimens are shown. These series were shocked under similar conditions with the most consistent difference being a slight difference in pulse duration and spot size. The longer pulse shots had a 1.5 cm diameter spot size and the shorter pulse shots had a 1.1 cm diameter spot. The hardness at the center of the disc thickness was 5 to 20 DPH higher than the surface hardness for each specimen with only one exception. This was expected as a result of superposition of the pressure waves generated at the opposite surfaces. The mid-thickness hardness is plotted in Figure 5. Although the pulse length appears to have little effect on the resultant hardness, the longer pulse results lie slightly below the short pulse results. There was no hardness correlation with peak pressure within the pressure range studied.

The hardness increases appear to be larger in the Ti-11V and Ti-15V alloys than in the others for both shocking configurations. This might be due to transformation of retained β to martensite by the shock wave. According to the calculations performed for these two configurations, as presented in Reference 6, the split beam arrangement produces higher pressures compared to the tungsten back-up arrangement if all other conditions are the same. However, in the two alloys shocked in both configurations the tungsten back-up produced a higher hardness level. Whether this is a result of the longer pulse length in the back-up experiments is not clear.

The furnace cooled alloys were shocked using the split beam configuration only. The results are shown in Figure 6 with the average surface hardness being plotted rather than mid thickness hardness (not measured in these specimens). The hardness of annealed titamium sheet is included in

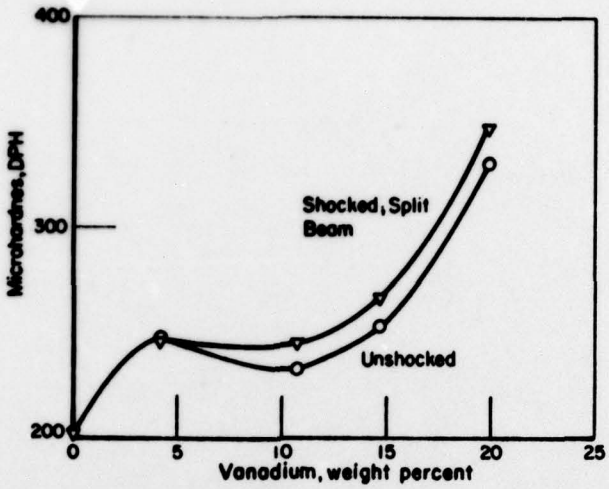

FIGURE 6. CHANGE IN HARDNESS AFTER LASER SHOCKING HOMOGENIZED AND FURNACE COOLED ALLOYS IN THE SPLIT BEAM CONFIGURATION

The pulse duration was 30 ns and the peak pressures ranged from 7.2 to 7.4 GPa.

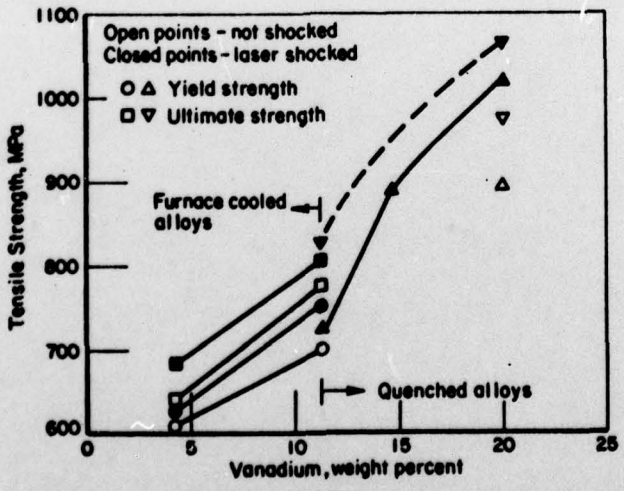

FIGURE 7. THE EFFECT OF LASER SHOCKING ON THE TENSILE PROPERTIES OF FURNACE COOLED AND OF QUENCHED ALLOYS

The peak pressures lie in the range of 7.6 to 8.2 GPa.

this figure. Except for the Ti-4V alloy, the surface hardness was increased after laser shocking by about the same amount in each alloy.

This increase in hardness is probably due to shock induced strain hardening of the α and β phases present in these alloys.

It is of interest to compare the hardness of the quenched and the furnace cooled alloys without laser shocking. The pronounced peak in hardness at Ti-15V in the quenched condition is typical of strengthening by a fine precipitate of ω phase, indicating that ω is present in these alloys. This peak is absent in the furnace cooled alloys. The increasing hardness with increasing vanadium in the furnace cooled alloys may be caused by both a solid solution strengthening effect and by the refinement of the $\alpha + \beta$ microstructure at higher vanadium content.

Tensile Properties

In addition to hardness, it was of interest to investigate the effect of laser shocking on the tensile properties of these alloys. The tensile specimens were irradiated using a split beam arrangement and black paint plus quartz overlay. The average pulse duration was 24 ns. Two separate overlapping laser shots were required to cover the entire gage length of each specimen. The quenched specimens were all slightly warped by quenching stresses even after machining.

Each alloy was not laser shocked in both heat treat conditions. The quenched strip was quite warped and the Ti-4V material was not suitable for tensile specimens. The higher vanadium compositions were of interest in the quenched condition because metallography showed these alloys to be strain transformable. Therefore they should respond well to laser shock hardening. Furnace cooled specimens of Ti-4V and Ti-10V were laser shocked and tensile tested.

The results are presented in Table 1 and the average strengths are plotted in Figure 7. The furnace cooled alloys were the most ductile and gave the most consistent results. Both the yield and ultimate strength were increased by laser shocking. It is expected from the data trend that the higher vanadium alloys would behave similarly. Note that the tensile strength of the Ti-4V alloy was increased whereas the hardness was not (Figure 6).

TABLE 1. THE EFFECT OF LASER SHOCKING ON THE TENSILE PROPERTIES OF Ti-V ALLOYS

Alloy	Condition			Tensile Properties		
	Heat Treatment	Laser Shocked	Peak[(a)] Pressure GPa	0.2% Offset Yield Strength MPa	Ultimate Strength MPa	Total Elongation
Ti-4V	Furnace cooled	No	0	612	642	0.03
Ti-4V	Furnace cooled	No	0	607	641	0.03
Ti-4V	Furnace cooled	Yes	8.2	645	708	0.09
Ti-4V	Furnace cooled	Yes	7.8	608	669	0.10
Ti-11V	Furnace cooled	No	0	676	751	0.17
Ti-11V	Furnace cooled	No	0	719	800	0.14
Ti-11V	Furnace cooled	Yes	8.0	767	830	0.16
Ti-11V	Furance cooled	Yes	8.0	735	779	0.02
Ti-11V	Brine quenched	No	0	--	455	--
Ti-11V	Brine quenched	Yes	8.0	728	800	0.03
Ti-11V	Brine quenched	Yes	8.0	726	854	0.17
Ti-15V	Brine quenched	No	0	--	348	--
Ti-15V	Brine quenched	No	0	--	685	--
Ti-15V	Brine quenched	Yes	8.2	888	888	--
Ti-20V	Brine quenched	No	0	814	912	0.10
Ti-20V	Brine quenched	No	0	995	1035	0.04
Ti-20V	Brine quenched	Yes	7.6	993	1034	0.05
Ti-20V	Brine quenched	Yes	8.0	1044	1093	0.04

(a) Average peak pressure for the two separate irradiations of each specimen. The average pulse duration was 24 ns.

The quenched Ti-11V and Ti-15V alloys were too brittle in the unshocked condition to give reliable tensile properties (Table 1). However, after laser shocking these alloys had sufficient ductility to provide some tensile properties data. This "ductilizing" effect of laser shocking might reflect an in-material effect or it might just be a consequence of the laser shock induced plastic strain relieving the quenching stresses before tensile testing. The latter possibility is more likely because the Ti-20V showed no increase in total elongation after laser shocking.

The only indication of the strengthening influence of laser shocking on the quenched materials is shown by the Ti-20V alloy, in which the tensile strength increased by about 10 percent. The strength shown for the Ti-15V alloy is suspect both because the hardness showed a peak at this composition and the plastic strain at fracture was very small.

Over-all it is clear that laser shocking increases the hardness and strength of the Ti-V alloys. The results suggest that laser shock strengthening may be especially effective on the metastable,strain transformable alloys.

CONCLUDING DISCUSSION

During this program the extended computer analysis indicated that peak pressures well above 10 GPa were being reached with both the tungsten back-up plate and with the split beam arrangement on the thin discs. These are higher pressures than have been calculated previously for laser induced shock waves.

High amplitude stress waves caused significant increases in the hardness and tensile strength of each of the Ti-V alloys, but the greatest changes require the pressure enhancement arrangements of either a high impedance back-up plate or simultaneous shocking of both specimen surfaces using the split beam arrangement.

The hardness and strength effects were obviously due to shock induced microstructural changes. These changes are certainly a combination of strain hardening from laser shock induced dislocations and possible twinning, and strain-induced martensite,depending on the alloy and heat treatment. The magnetic susceptibility measurements did not show any effect of laser shocking. The limited amount of transmission microscopy which could be performed did not show any evidence of shock induced phase transformations in the quenched alloys. The microstructures studied were

consistent with shock strain hardening and possibly a shock induced martensitic transformation of the metastable retained β in the quenched alloys. It is probable that the enhanced laser shock pressures and durations reached in this program were still too low to create the phase transformations involving $\alpha \rightleftarrows \omega$ or $\beta \rightleftarrows \omega$ discussed in the introduction.

More detailed electron transmission microscopy, x-ray diffraction, and other analytical studies of the laser shocked Ti-V alloys would be necessary to show definitively what the actual mechanisms of laser shock interactions with these titanium alloys are. However, the results of this investigation show that there can be substantial in-material effects during irradiation of Ti-V alloys by a high energy pulsed laser beam, and these effects influence the mechanical properties of the alloys.

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